J/ψ production in p+p, d+Au and Au+Au collisions measured by PHENIX at RHIC

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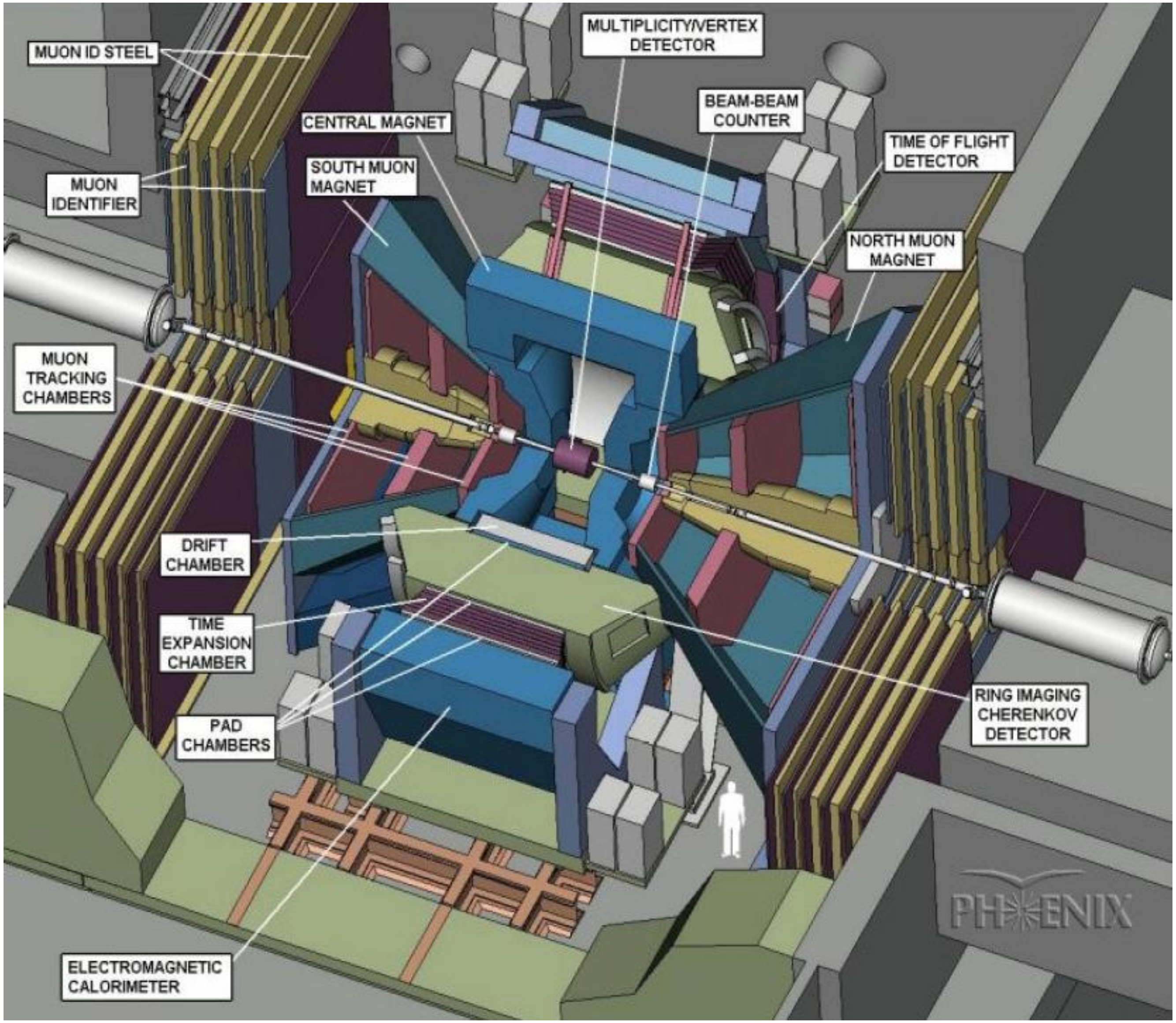
Outline

- Introduction: PHENIX spectrometer
- p+p collisions: baseline for d+A and A+A collisions
- d+Au collisions: cold nuclear matter effects
- Cu+Cu and Au+Au: hot matter effects

Introduction

J/ψ measurements in PHENIX (1)



Central arm

$J/\psi \rightarrow e^+e^-$

$p > 0.2$ GeV/c

$|y| < 0.35$

$\Delta\Phi = \pi$

Muon arms

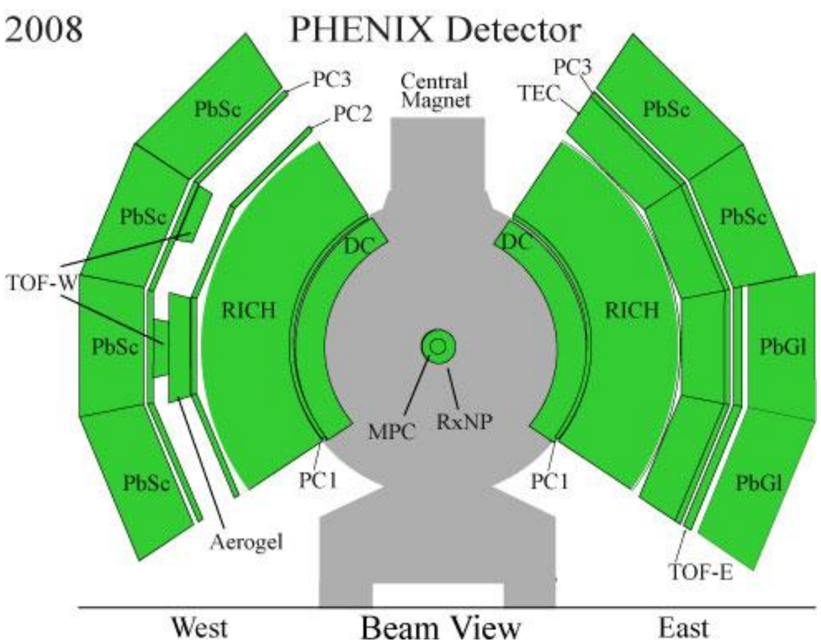
$J/\psi \rightarrow \mu^+\mu^-$

$p > 2$ GeV/c

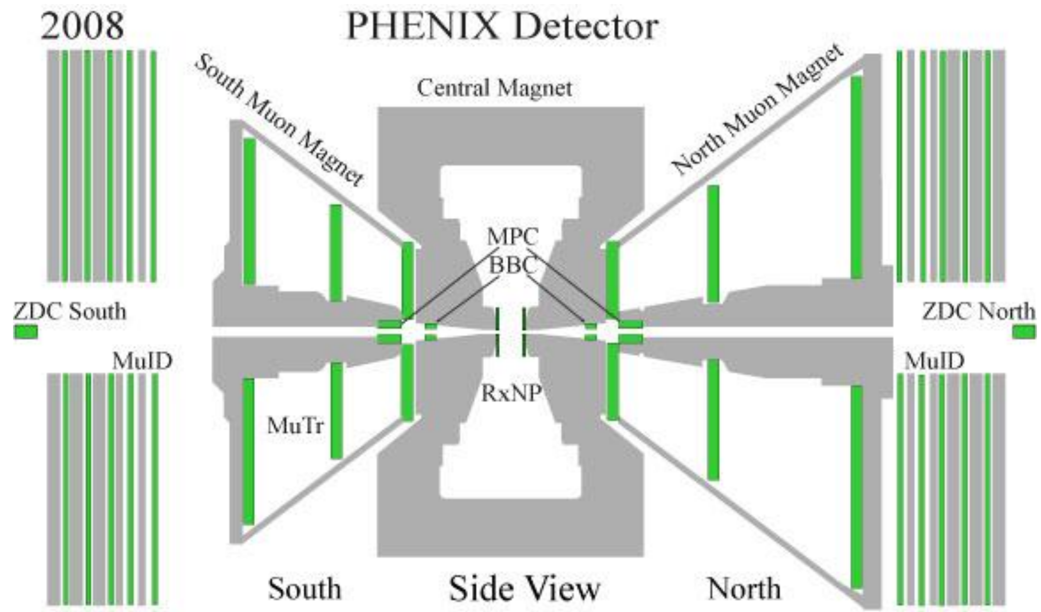
$|y|$ E [1.2,2.4]

$\Delta\Phi = 2\pi$

J/ψ measurements in PHENIX (2)



Mid rapidity: $J/\psi \rightarrow e^+e^-$

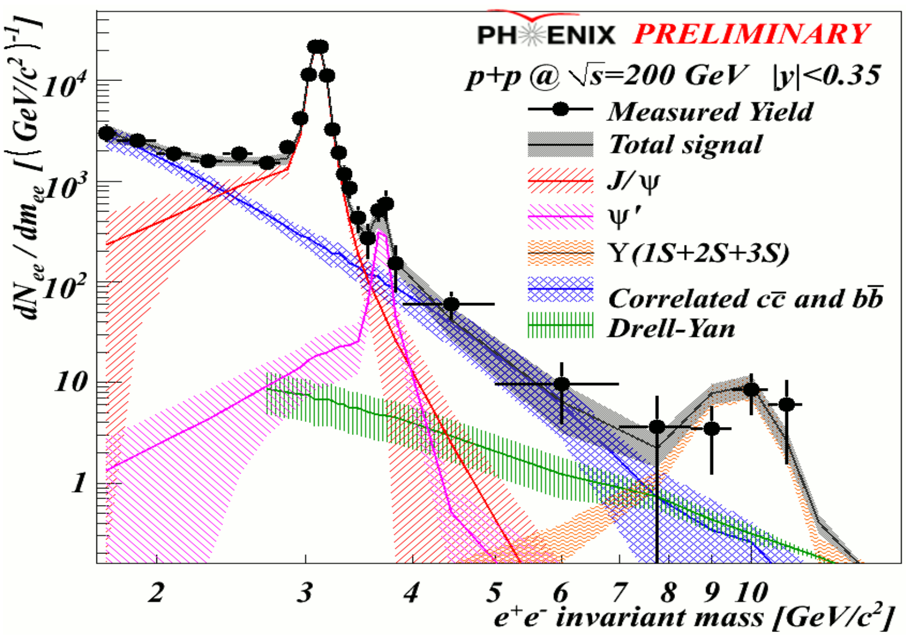


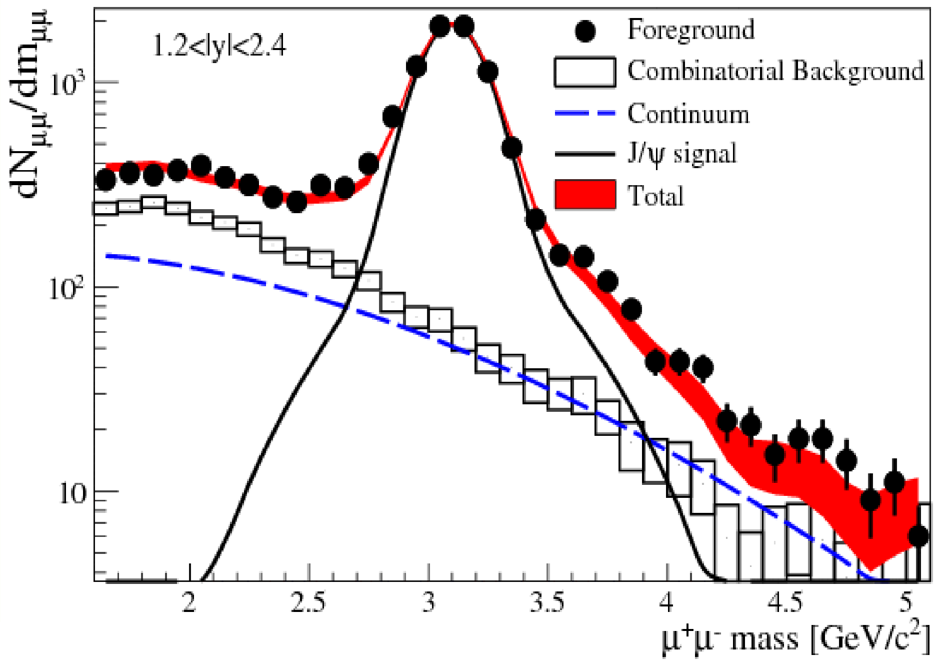
Forward rapidity: $J/\psi \rightarrow \mu^+\mu^-$

Electrons identified using RICH and EMCAL; tracked using pad and drift chambers

Muons identified using layered absorber + Iarocci tubes; tracked using 3 stations of cathode strip chambers, in radial magnetic field

di-lepton invariant mass distributions





Mid rapidity: J/ψ → e^+e^-

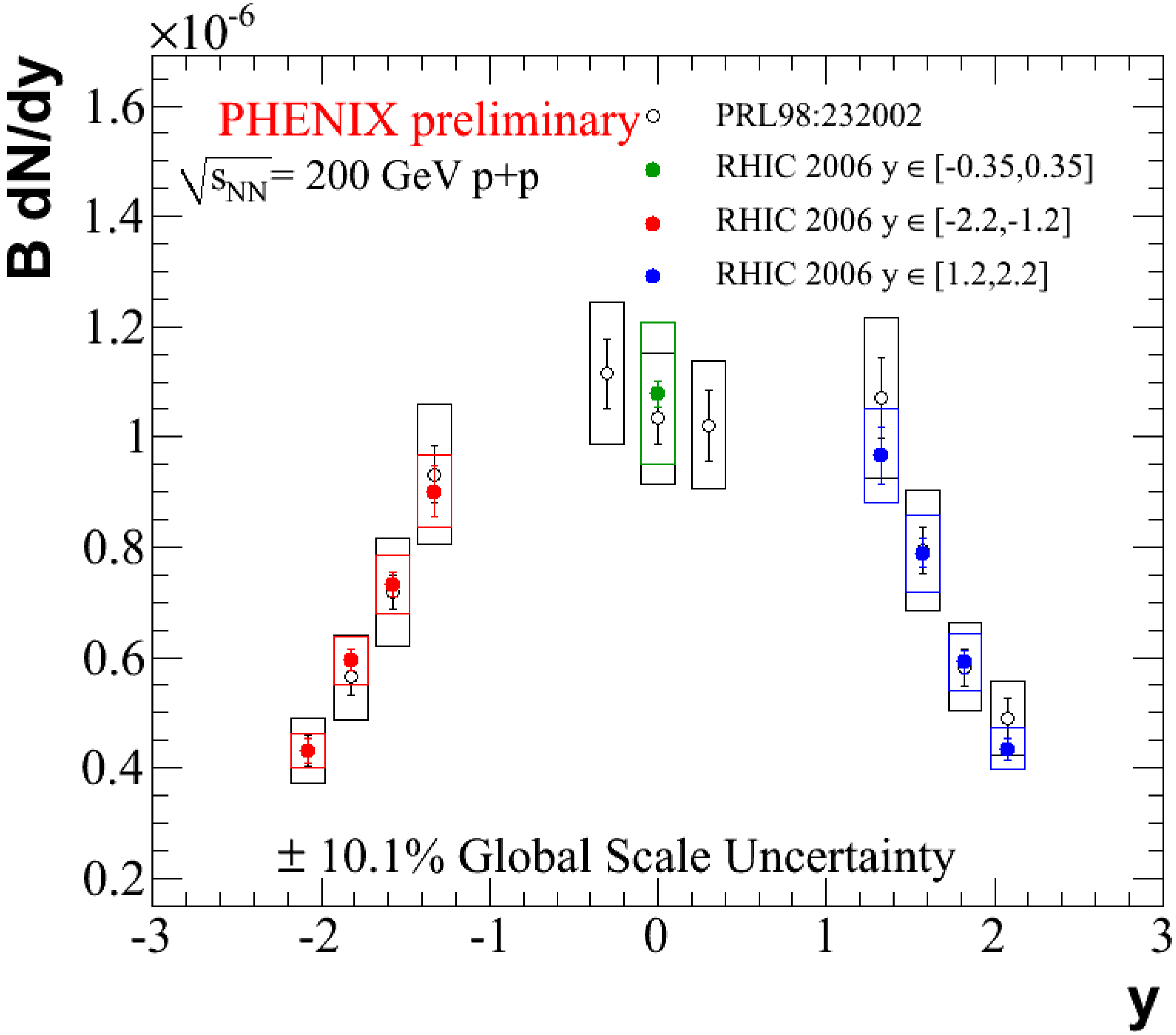
J/ψ mass resolution ~ 60 MeV

Forward rapidity: J/ψ → $\mu^+\mu^-$

J/ψ mass resolution ~ 170 MeV

I. p+p collisions:
Baseline for d+A and A+A collisions

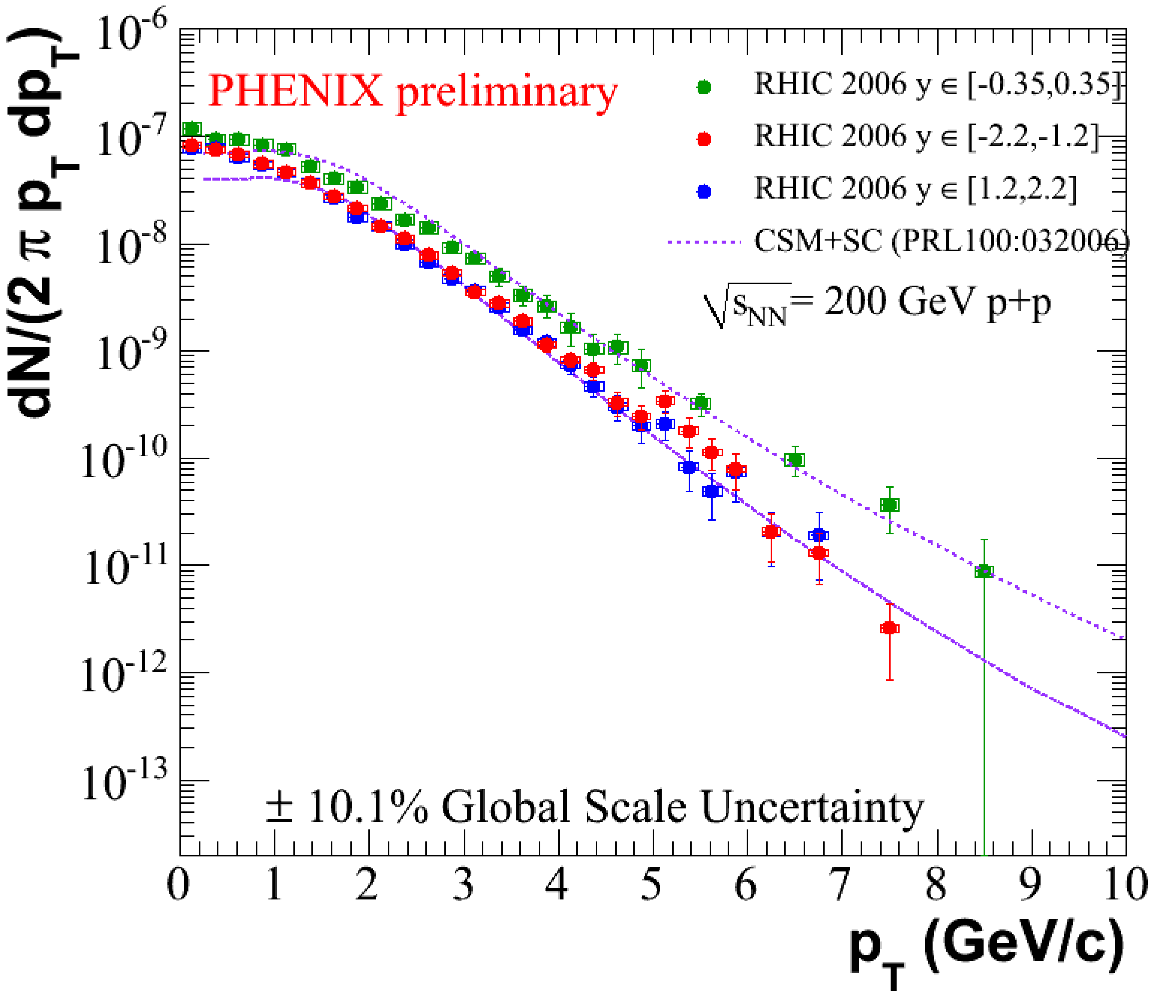
J/ψ production cross section vs rapidity



Higher statistics and better control over systematic uncertainties.

Excellent agreement with published results.

J/ψ production cross section vs p_T



Excellent agreement between data at positive and negative rapidity.

Harder spectra observed at mid-rapidity.

Lines correspond to **one** calculation of J/ψ p_T distributions, namely: CSM (LO)+S channel cut

PRL 100, 032006 (2008)

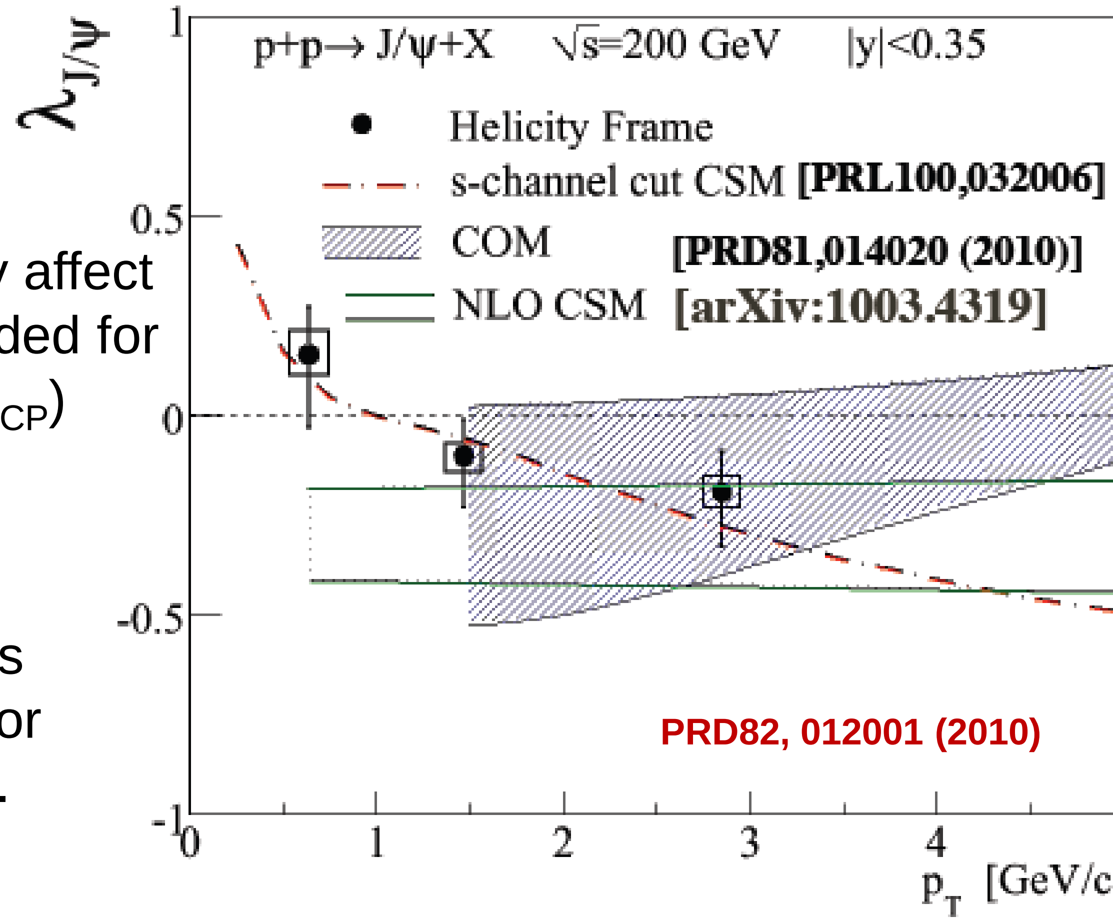
J/ψ polarization (λ_θ)

J/ψ polarization measurements are important

- theoretically to understand production mechanism
- experimentally, because they affect acceptance calculations needed for cross-sections and R_{AA} (or R_{CP})

All results shown in this presentation assume $\lambda_\theta = 0$. No additional systematic errors have been added to account for possible non zero polarization.

J/ψ polarization (λ_θ) measured at mid-rapidity in the helicity frame



II. d+Au collisions:
Cold nuclear matter effects

Cold nuclear matter effects (CNM)

Anything that can modify the production of heavy quarkonia in heavy nuclei collisions (as opposed to p+p) in absence of a QGP

Initial state effects:
- Energy loss of the incoming parton
- Modification of the parton distribution functions (npdf)
- Gluon saturation at low *x* (CGC)

Final state effects:
Dissociation/breakup of the J/ψ (or precursor $c\bar{c}$ quasi-bound state)
Modeled using a break-up cross-section $\sigma_{breakup}$

Modified PDF (npdf)

npdf refer to the fact that parton distributions (as a function of x_{bj}) inside a nucleon differ whether the nucleon is isolated or inside a nuclei.

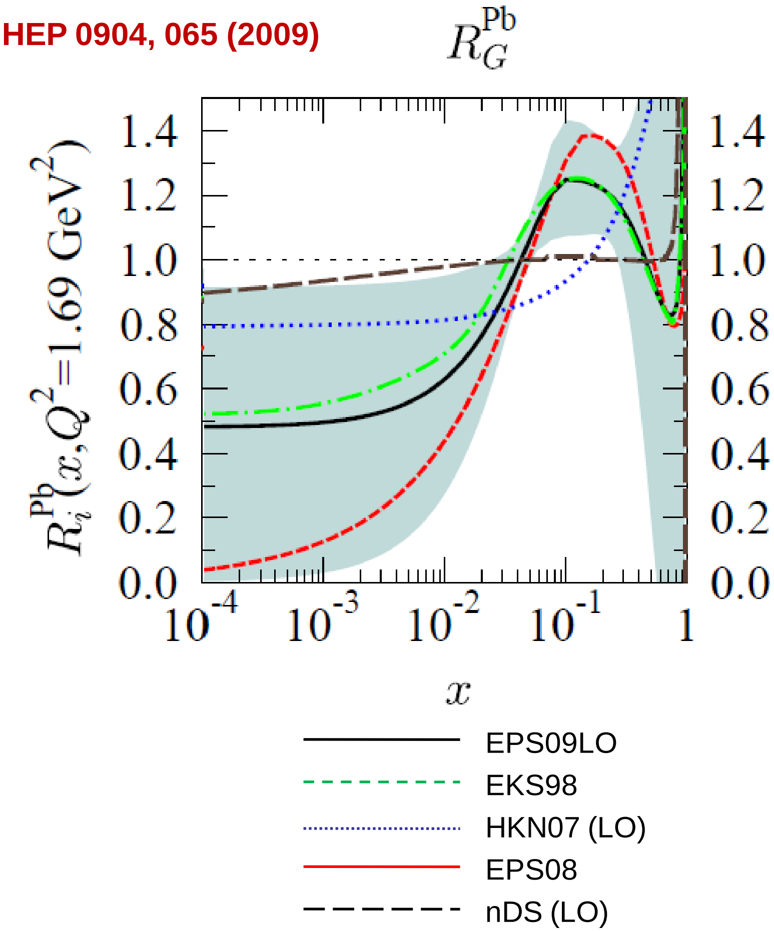
Gluon nuclear npdfs are poorly known, especially at low x (shadowing region).

Various parametrizations range from

- little shadowing (HKN07, nDS, nDSg)
- moderate shadowing (EKS98, EPS09)
- large shadowing (EPS08)

Grayed area correspond to uncertainty due to limited data available for constrain.

JHEP 0904, 065 (2009)

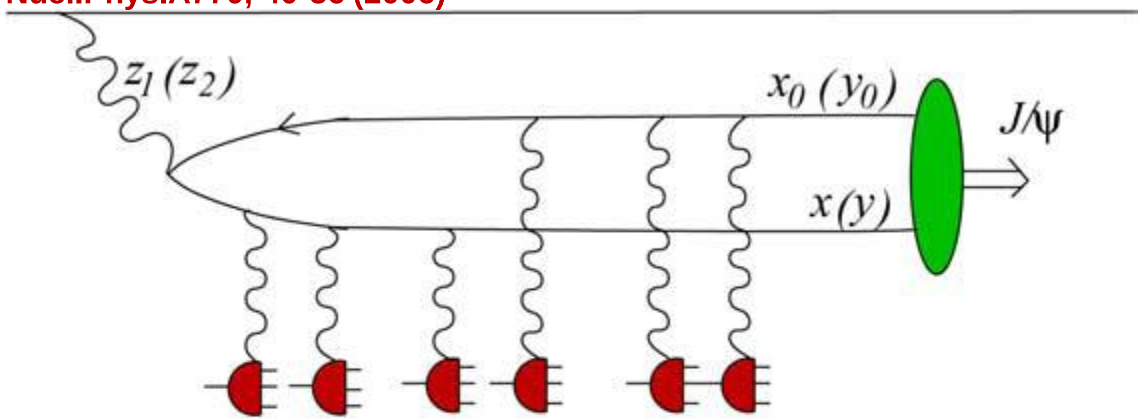


Gluon saturation

CGC provides a different picture of the d-Au collision and how J/ψ is produced

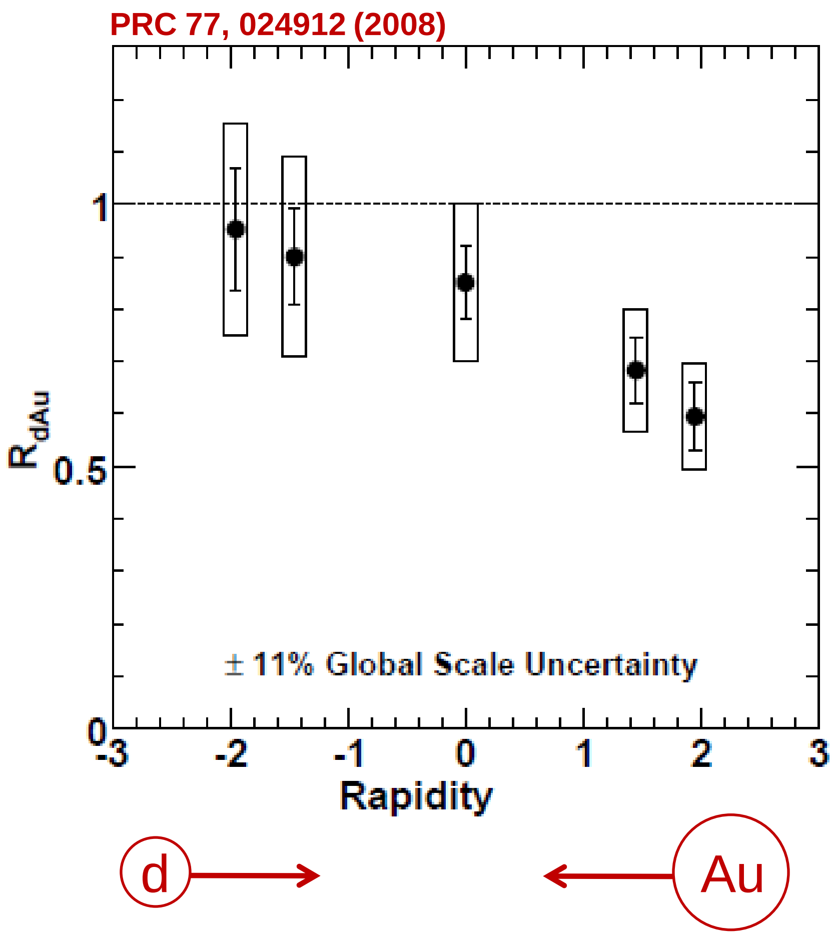
At low enough x_2 (in the target nuclei), the gluon wave functions overlap. The $c\bar{c}$ pair from the projectile parton interacts coherently with all nucleons from the target, resulting in the J/ψ formation.

Nucl.Phys.A770, 40-56 (2006)



This is applicable at low x_2 (forward rapidity) only;

J/ψ production in d+Au (1) 2003 data



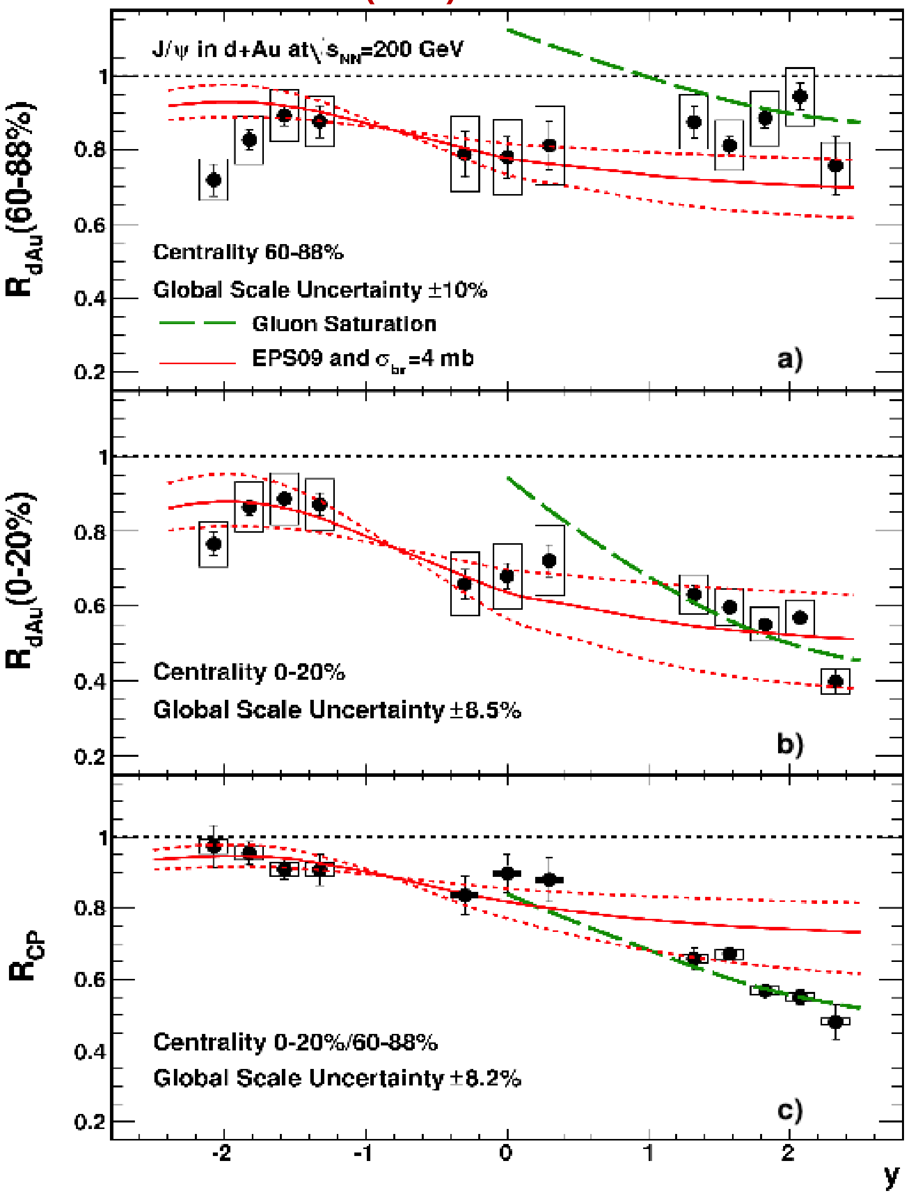
J/ψ nuclear modification factor in minimum bias d+Au collisions as a function of rapidity

y<0: Au going side. Large x (gluon momentum) in Au nuclei. Little to no modification is observed.

y>0: deuteron going side. Small x in Au nuclei. Suppression is observed, consistent with shadowing/saturation.

npdf + $\sigma_{breakup}$ vs (2008) data

arXiv:1010.1246 (2010)



npdf + breakup cross-section

- Take an npdf prescription (EPS09)
- Add a breakup cross-section
- Calculate CNM as a function of the collision centrality
- Compare to data.

At forward rapidity, this approach (red lines) cannot describe both the peripheral and the central data.

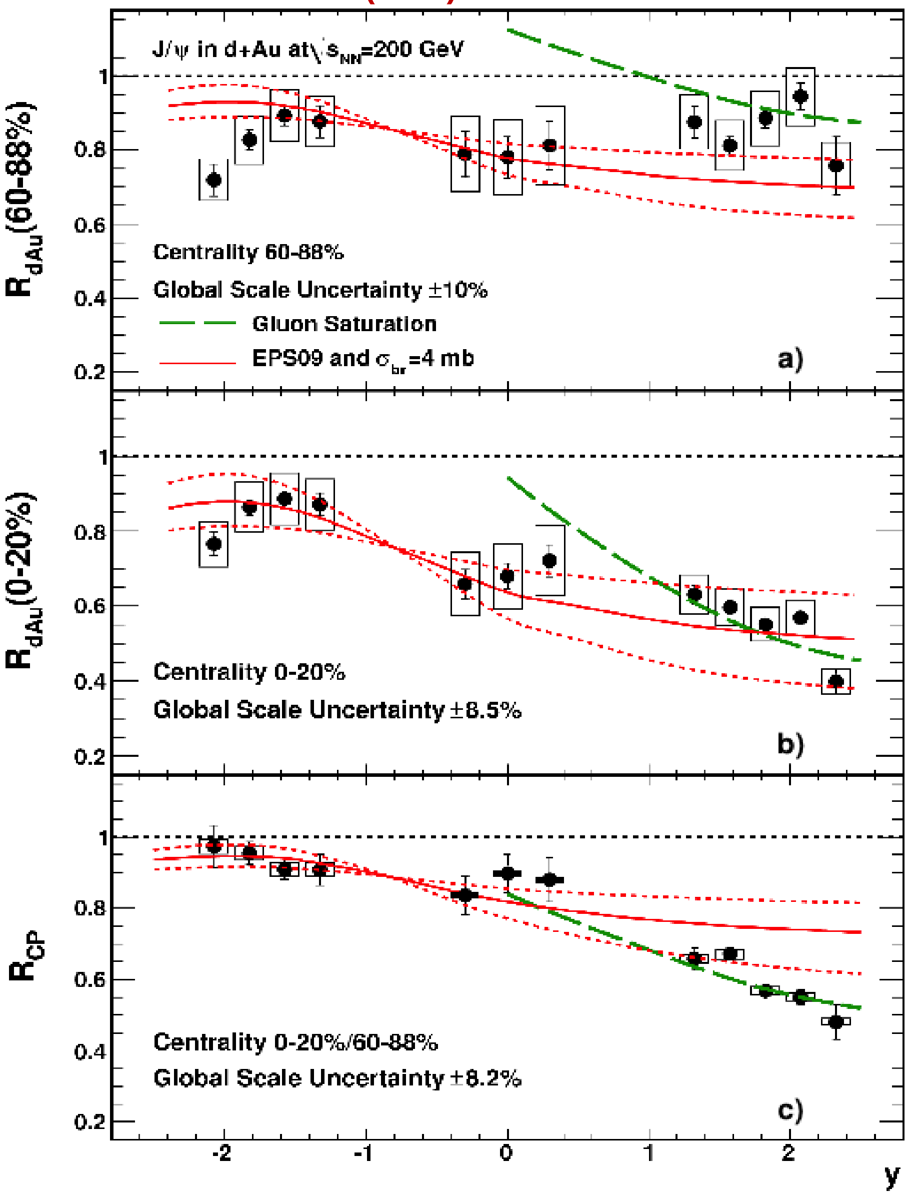
This is best illustrated by forming the ratio of the two (Rcp)

Color Glass Condensate:

On the other hand, data are reasonably well reproduced at forward rapidity by CGC (green lines) for all centralities.

npdf + $\sigma_{breakup}$ vs (2008) data

arXiv:1010.1246 (2010)



npdf + breakup cross-section

More remarks on the red lines:

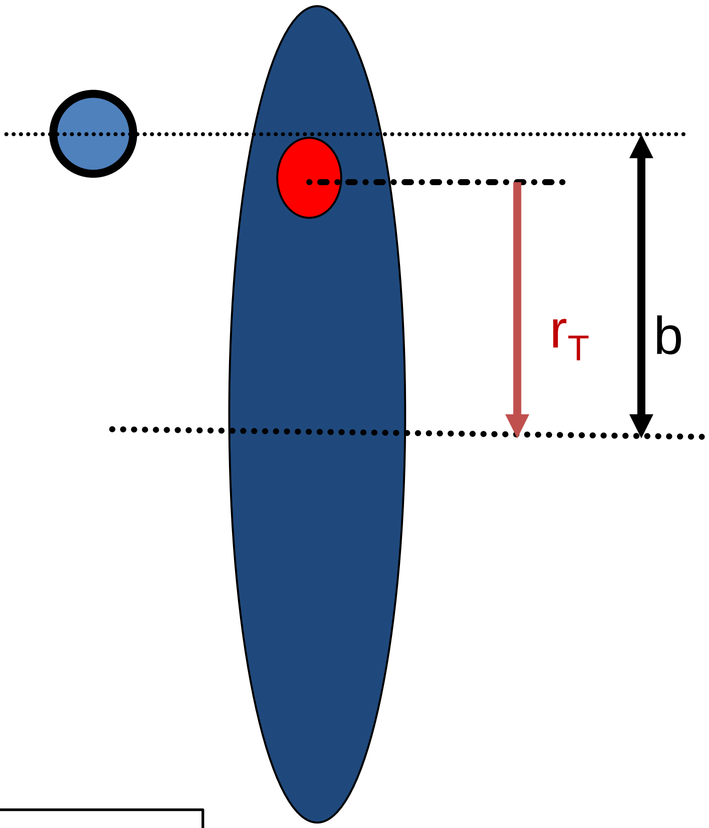
- These calculations are made assuming 2+1 production mechanism (aka intrinsic) for the J/ψ. Using 2+2 production mechanism (extrinsic) does not help, since this damp the rapidity dependency of the shadowing effect, missing the forward rapidity points even more.
- Other npdf sets, with extreme shadowing (namely EPS08) do a better job at reproducing the most central forward rapidity points but also fail for peripheral collisions.

Centrality dependence of CNM effects (1)

Measuring J/ψ R_{dA} for several centrality bins allows one to test the dependency of the available calculations on centrality.

It is expressed as a function of the (density weighted) longitudinal thickness $\Lambda(r_T)$ of the Au nucleus, with r_T the distance of the target nucleon to the nucleus center:

$$\Lambda(r_T) = \frac{1}{\rho_0}\int dz\rho(z, r_T)$$



For illustration:

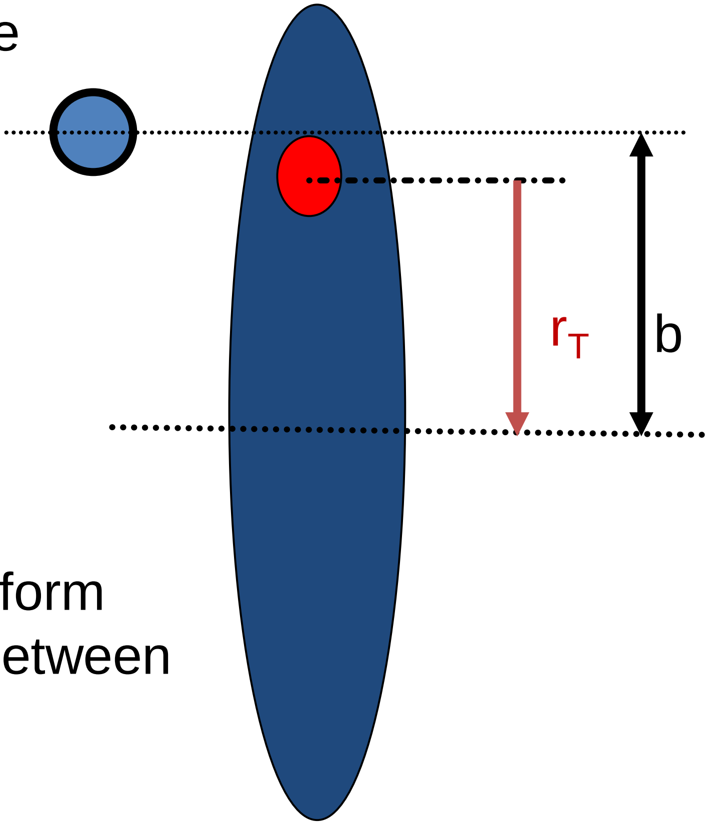
$$S^j_{P,\rho}(A,x,Q^2,\vec{r}) = 1 + N_\rho[S^j_P(A,x,Q^2) - 1].\frac{\int dz\rho_A(\vec{r},z)}{\int dz\rho_A(0,z)}$$

R. Vogt, arXiv:hep-ph/0411378v1

Centrality dependence of CNM effects (1)

One can assume several functional forms for the dependence of the J/psi suppression vs Λ(rt):

exponential:	$S(r_T) = e^{-a\Lambda(r_T)}$
linear:	$S(r_T) = 1 - a\Lambda(r_T)$
quadratic:	$S(r_T) = 1 - a\Lambda(r_T)^2$

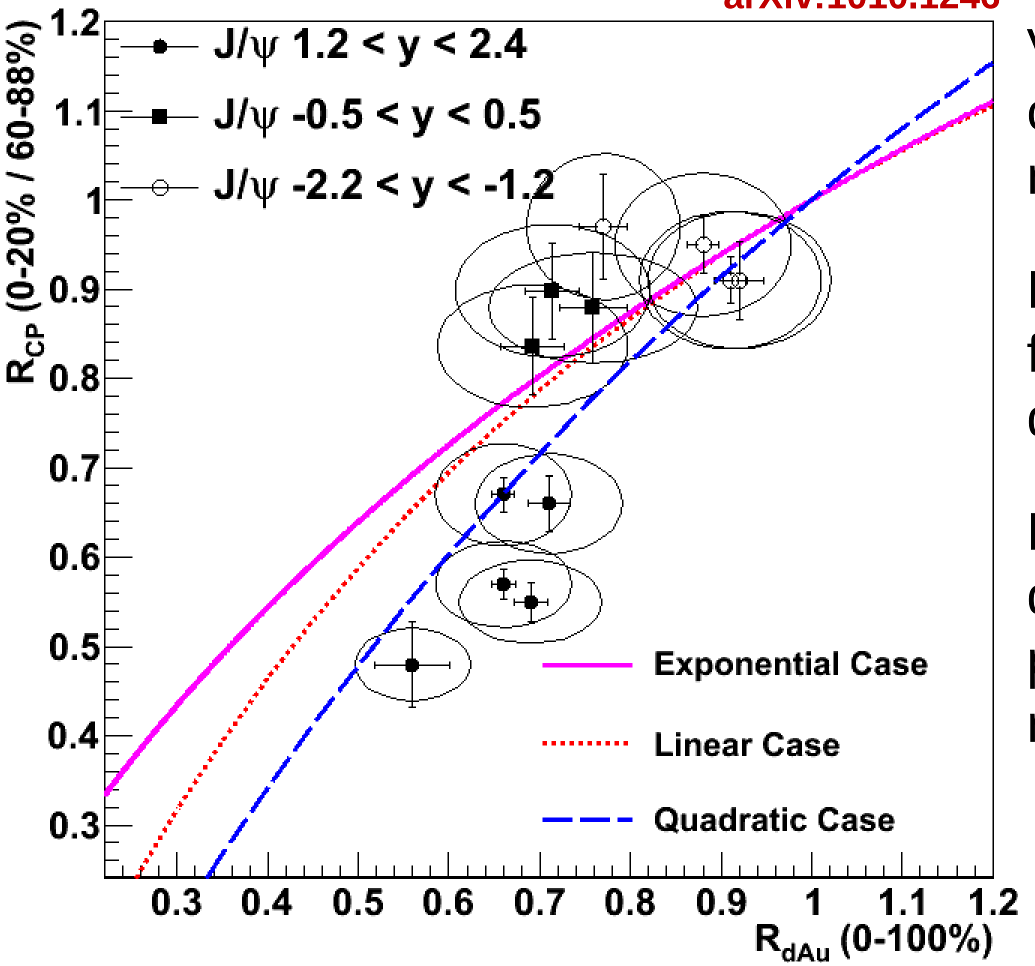


Knowing the distribution of r_T vs centrality, each form induces a unique (parameter free) relationship between R_{CP} and R_{dA} (in arbitrary centrality bins)

One can plot these relationships, and compare to data (as well as models)

Centrality dependence of CNM effects (2)

arXiv:1010.1246

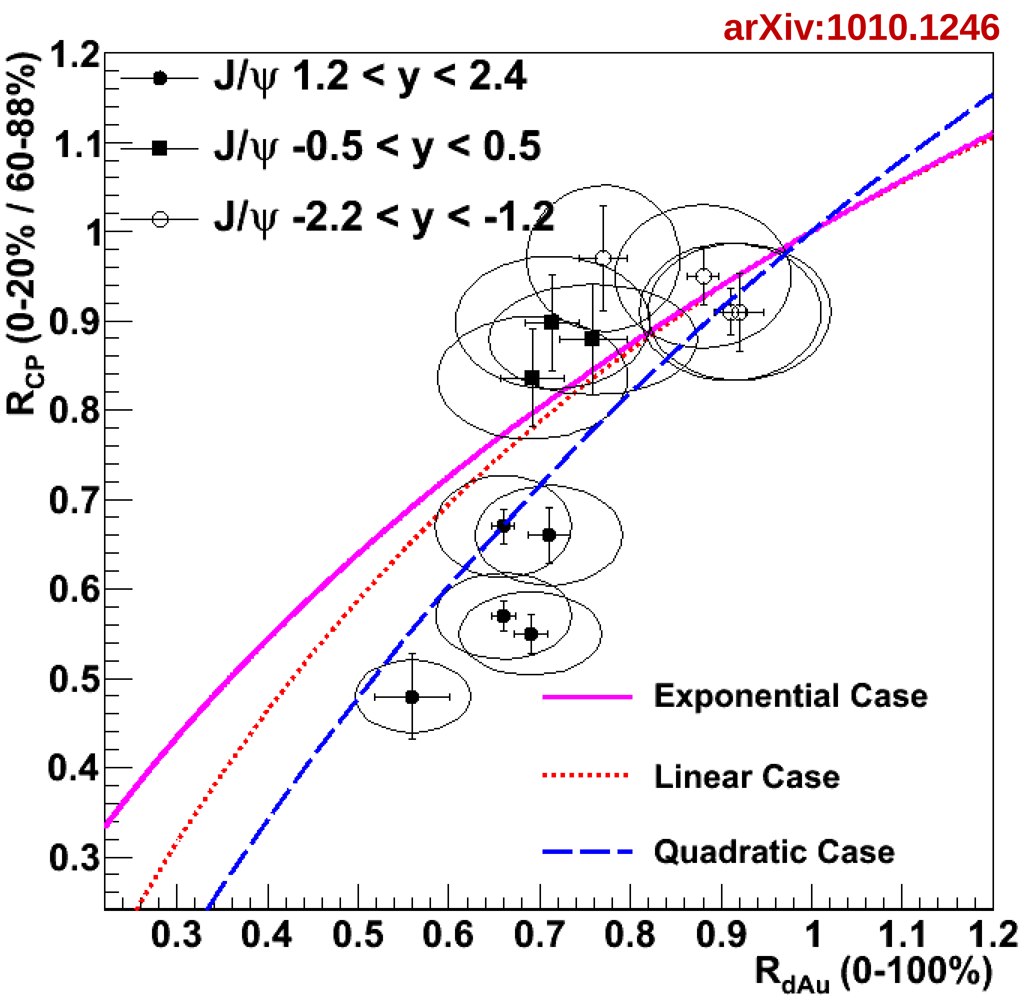


Various thickness dependencies chosen for illustration differ mostly at forward rapidity.

Mid and backward rapidity points favor exponential or linear dependency.

Forward rapidity data show a different behavior, possibly pointing to different (or additional) mechanism at play.

Centrality dependence of CNM effects (2)

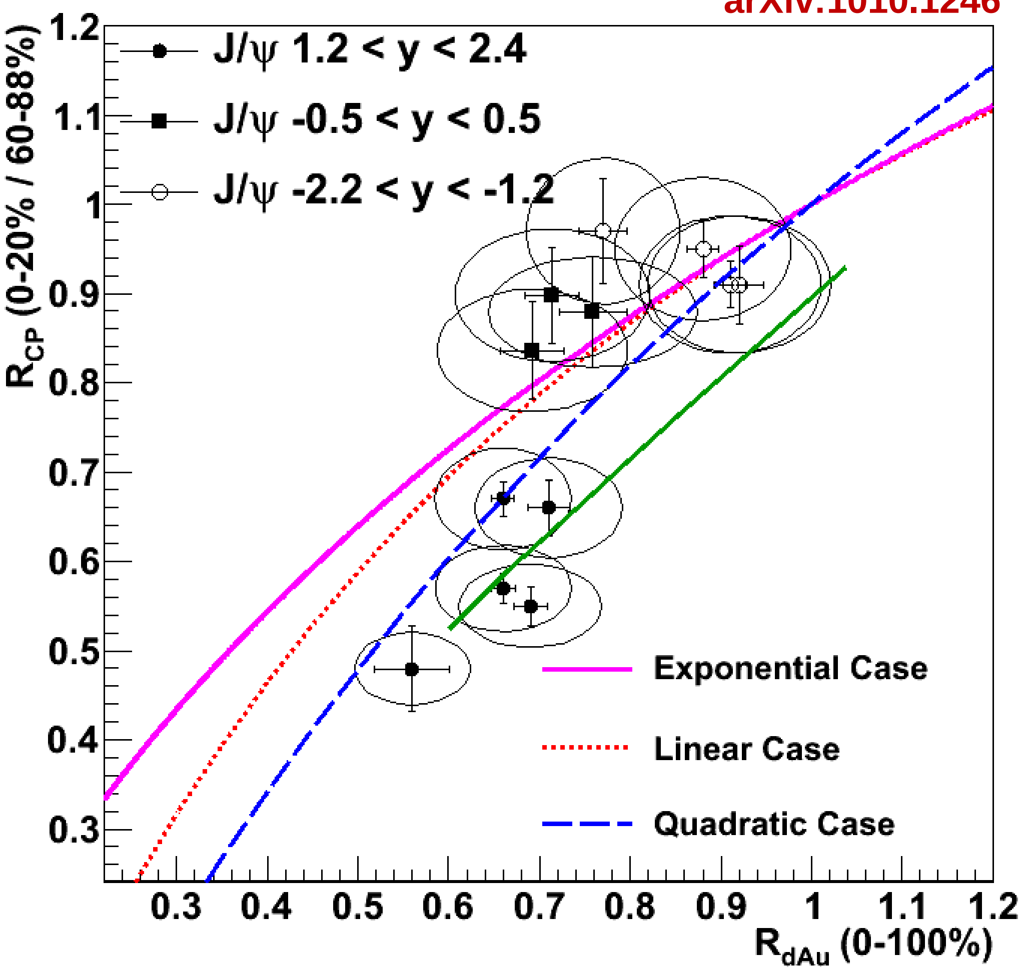


Use of npdf (EKS98, EPS09, etc.) to make centrality dependent predictions assumes <u>linear dependence</u>

Addition of break-up cross-section (usually) assumes <u>exponential dependence</u>

consequently, all such models lie between the red and the purple curve (and miss the forward rapidity points)

Centrality dependence of CNM effects (2)



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For comparison, one CGC calculation is shown here as a green line

Nucl.Phys.A770, 40-56 (2006)

Centrality dependence of CNM effects (3)

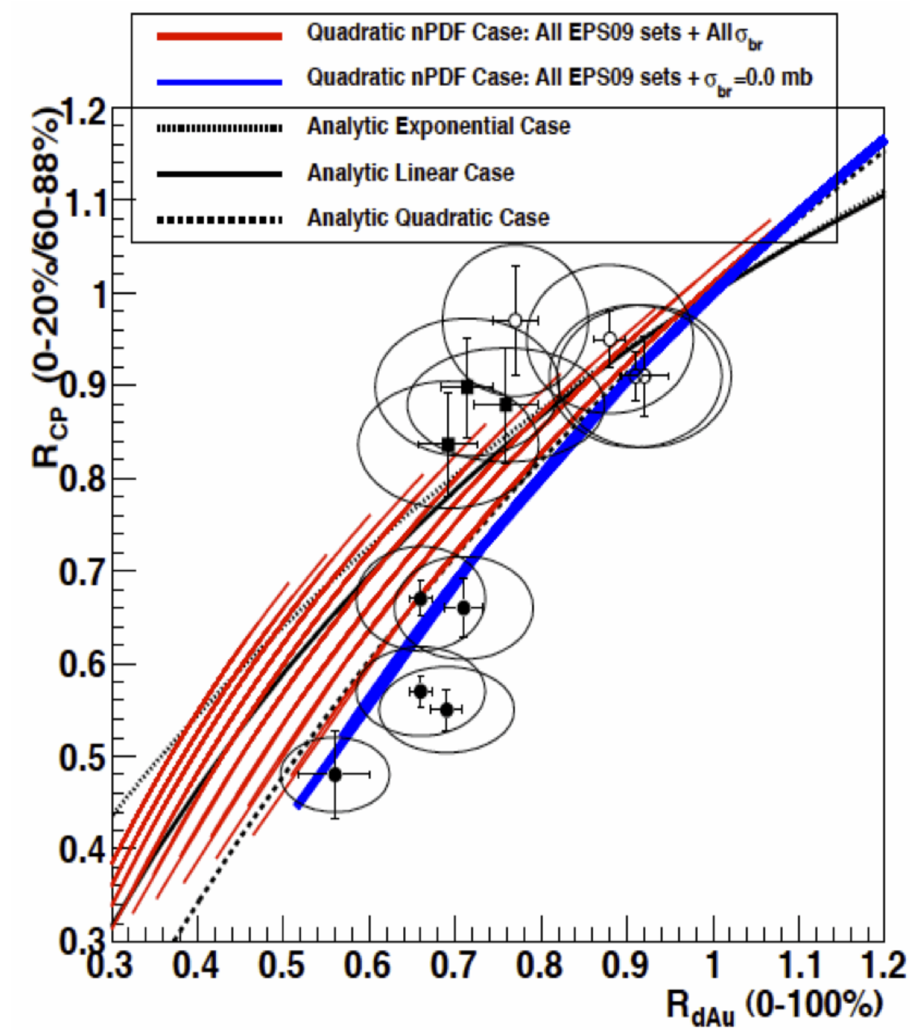
A complete (and more realistic) case study:

arXiv:1011.4534

This shows a Glauber calculation using a combination of EPS09 with <u>quadratic</u> $\Lambda(r_T)$ dependence, and a range of breakup cross sections.

EPS09 + Quadratic dependency reproduces the forward rapidity data reasonably well.

However, adding a significant breakup cross section (needed to get the right magnitude of the R_{AA}) worsens this agreement.



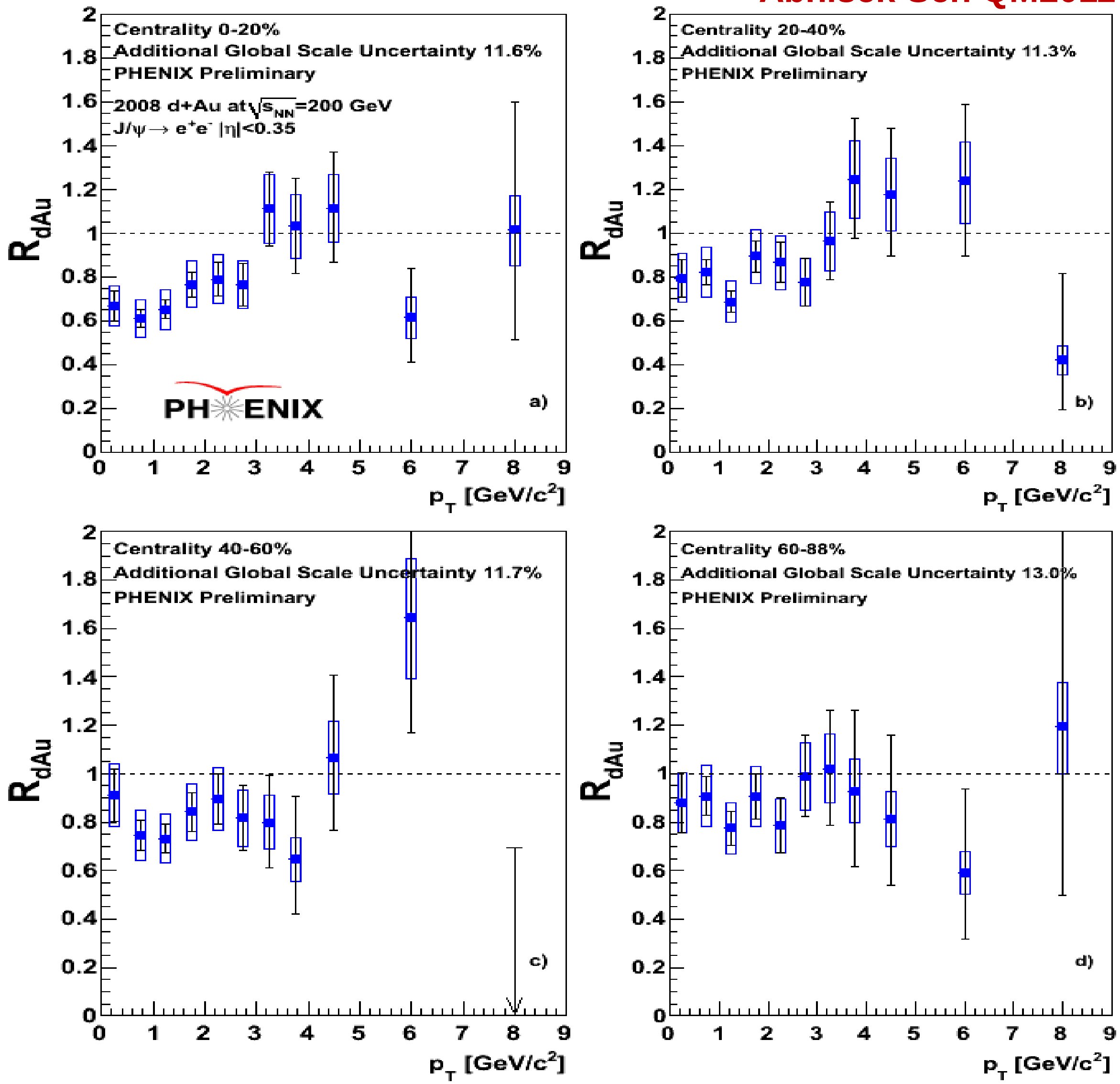
J/ψ production in d+Au (2) p_T dependency

Large statistics in 2008 d+Au data sample also allows detailed study of the p_T dependent R_{dAu}

Results at mid-rapidity show up to 30% suppression for low p_T, which vanishes for larger values.

Should also put strong constrains on CNM effects.

Abhisek Sen QM2011



III. A+A collisions:
Hot matter effects

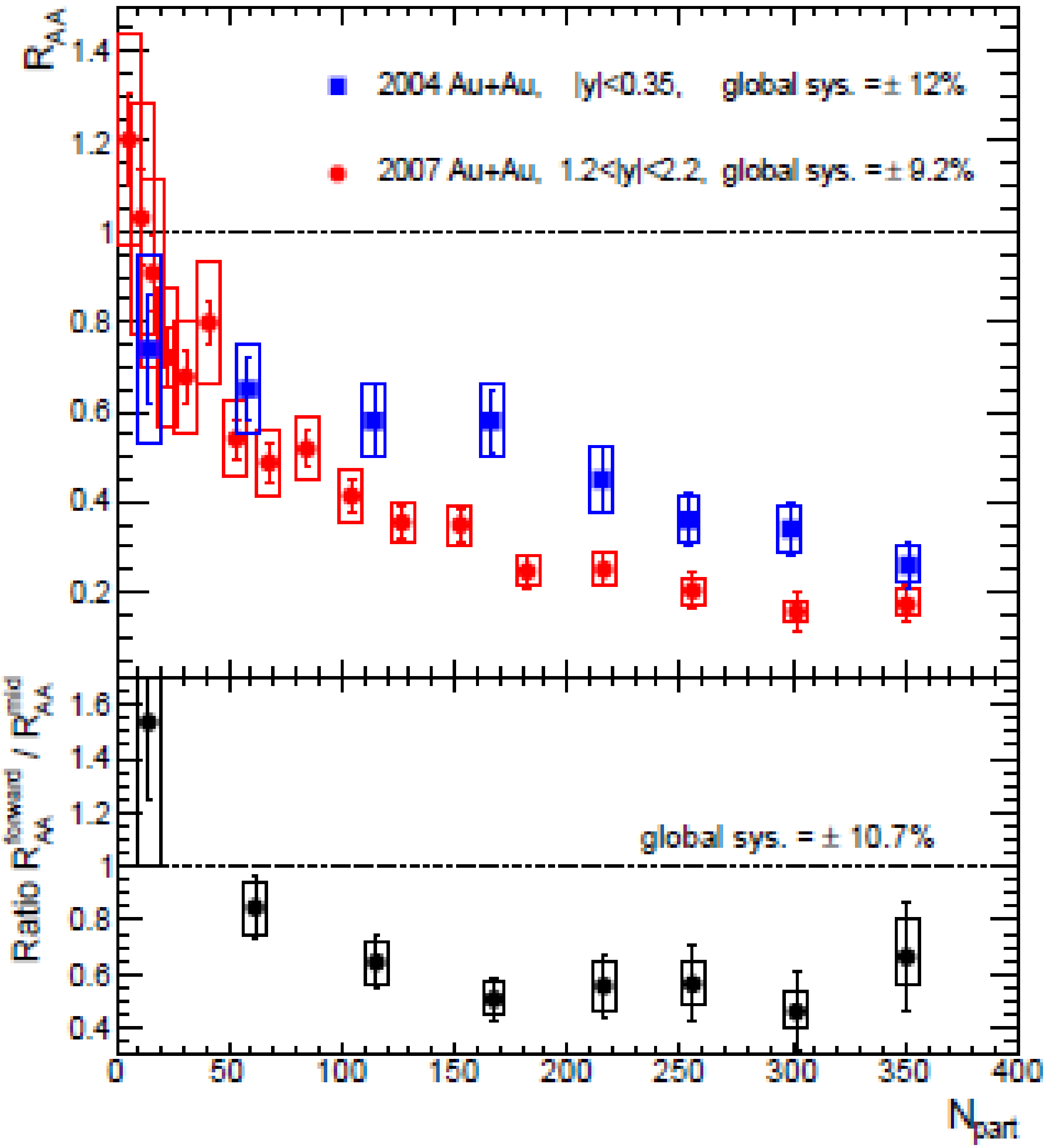
J/ψ R_{AA} vs N_{part} (1)

arXiv: 1103.6269

New results at forward rapidity obtained with 2007 data set are in perfect agreement with 2004 published data. (with about x4 in statistics)

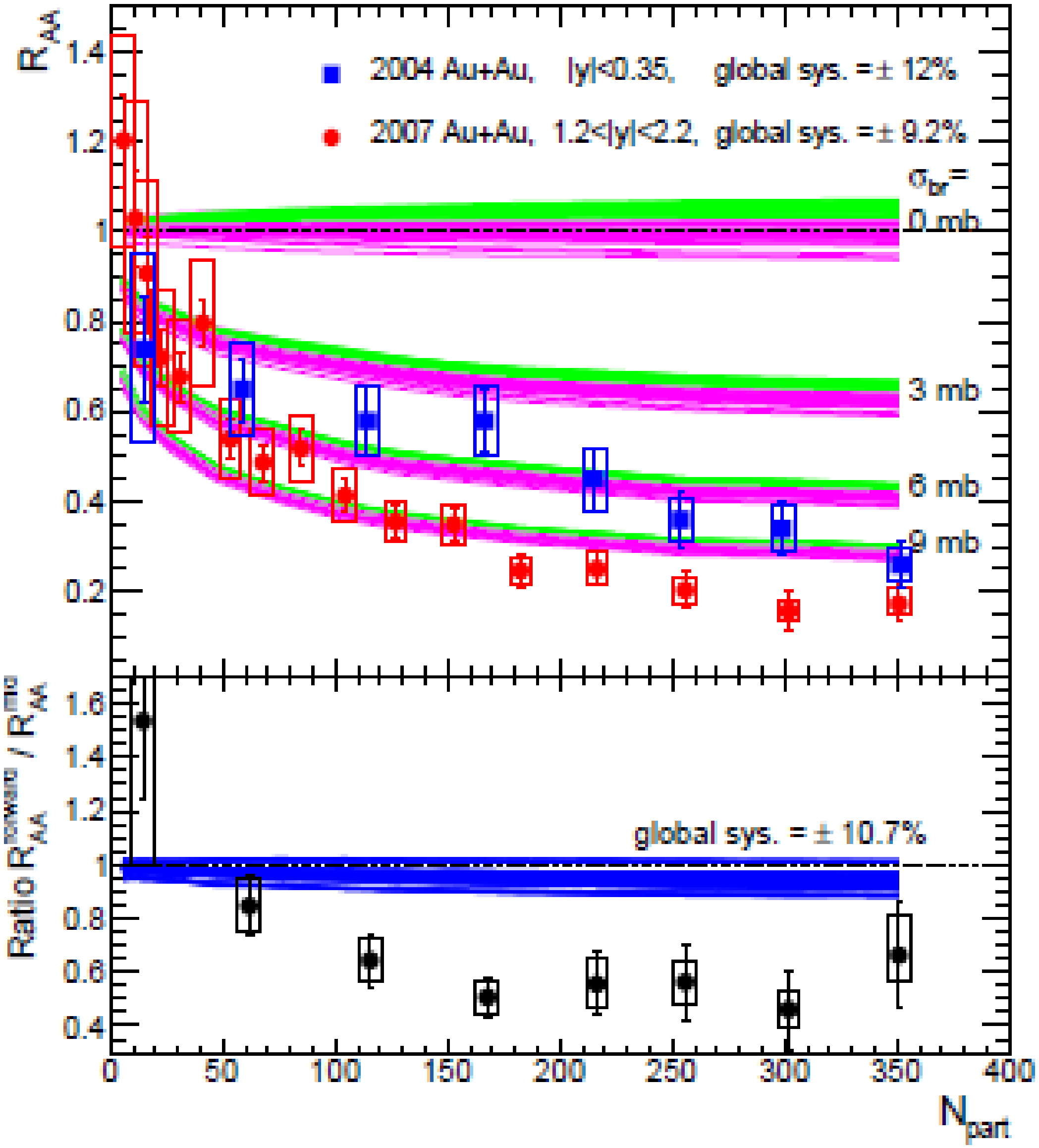
A suppression is observed for central collisions at both mid and forward rapidity.

Suppression is larger as forward rapidity than at mid rapidity, which is counter-intuitive, based on energy density arguments.



J/ψ R_{AA} and extrapolated CNM (1)

arXiv: 1103.6269



Lines use EPS09 combined with several values for $\sigma_{breakup}$

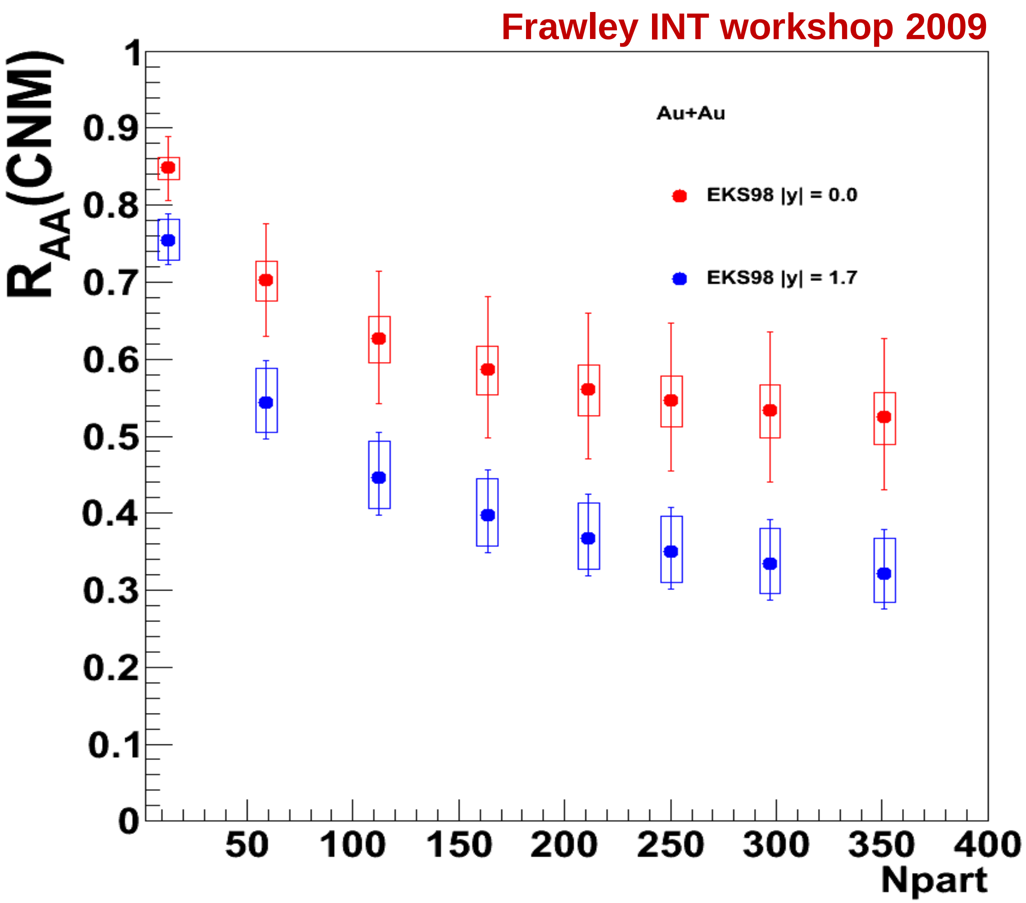
$\sigma_{breakup}$ values evaluated from 2008 d+Au data range from 2 to 4 mb, and cannot reproduce the Au+Au suppression.

Additionally, this CNM calculation (using a unique value for $\sigma_{breakup}$) shows little difference between mid and forward rapidity

However we've also seen that this approach cannot reproduce the d+Au data either.

J/ψ R_{AA} and extrapolated CNM (2)

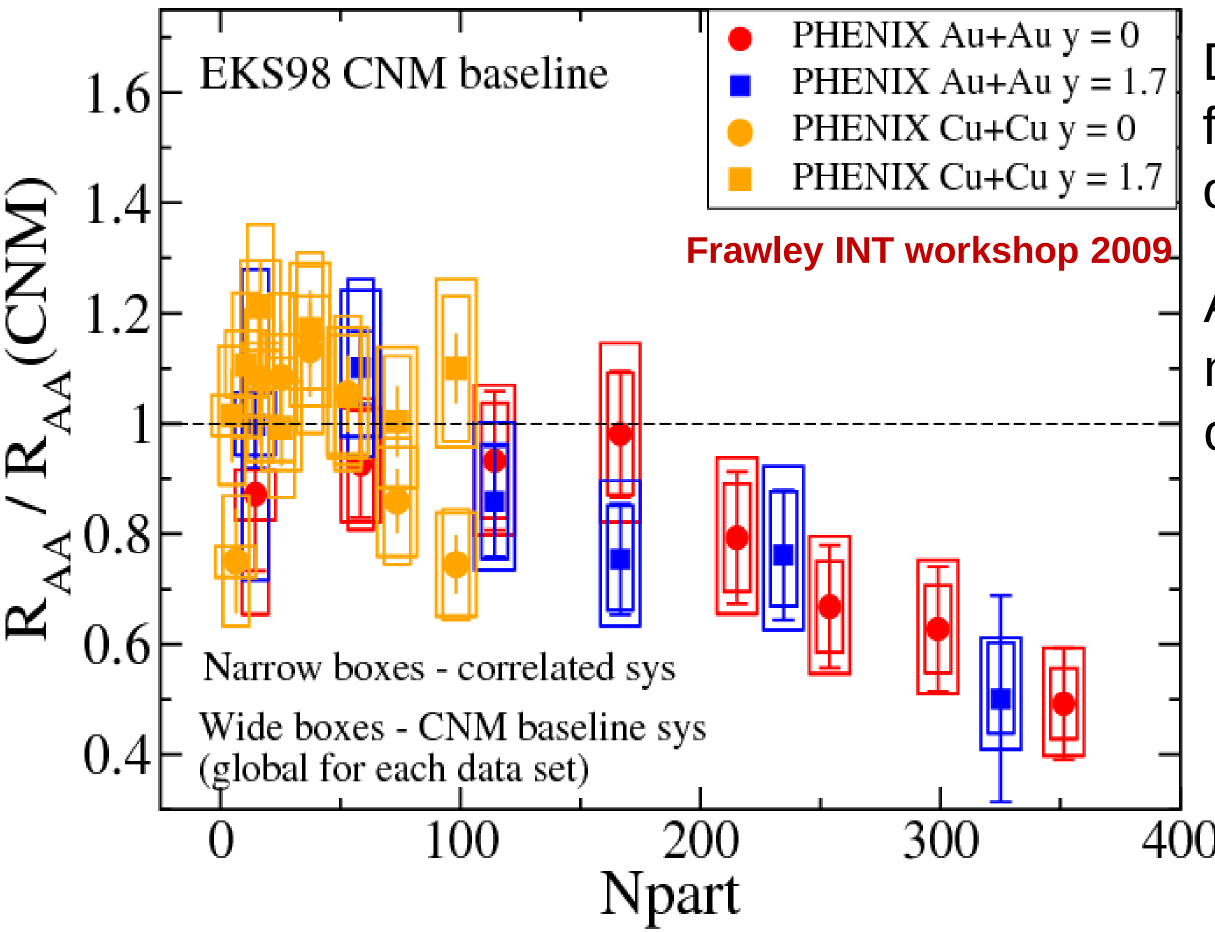
CNM effects estimated using 2008 d+Au dataset, EPS09 npdf, and <u>different</u> breakup cross-sections for mid and forward rapidity; extrapolated to Au+Au collisions.



The combination of a strong suppression observed in d+Au collisions at y>0, and little to no effect at y≤0 results in stronger suppression (from CNM) at forward rapidity in Au+Au collisions

J/ψ R_{AA} over CNM in Cu+Cu and Au+Au

$R_{AA}/R_{AA}(\text{CNM})$ vs N_{part}
using extrapolated CNM from previous slide



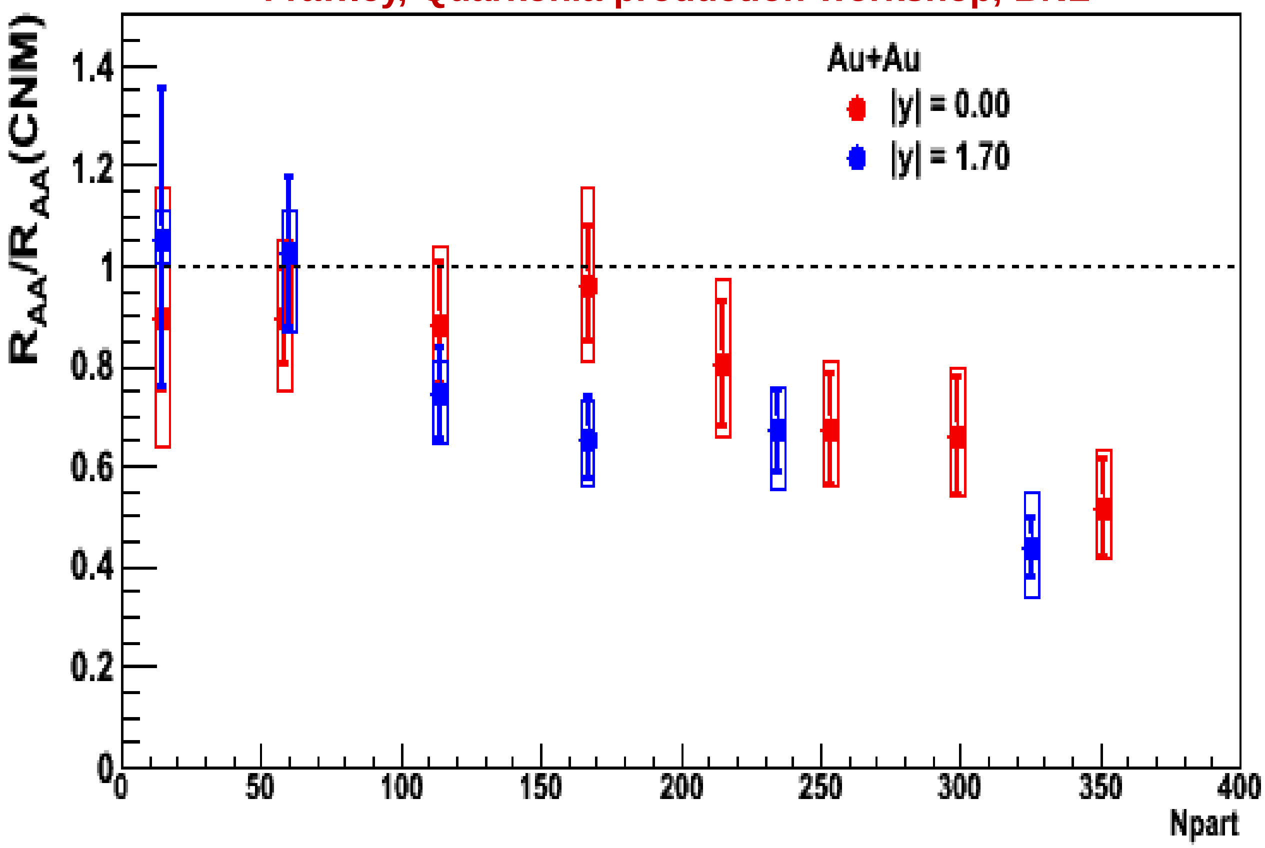
Differences between mid and forward rapidity are washed out.

A suppression beyond cold nuclear matter effects is still observed.

J/ψ R_{AA} over CNM in Cu+Cu and Au+Au

The conclusion from previous slide still holds with updated calculations, based on fits to the d+Au data that adjust both the break-up cross-section and the centrality (e.g. path length) dependency.

Frawley, Quarkonia production workshop, BNL



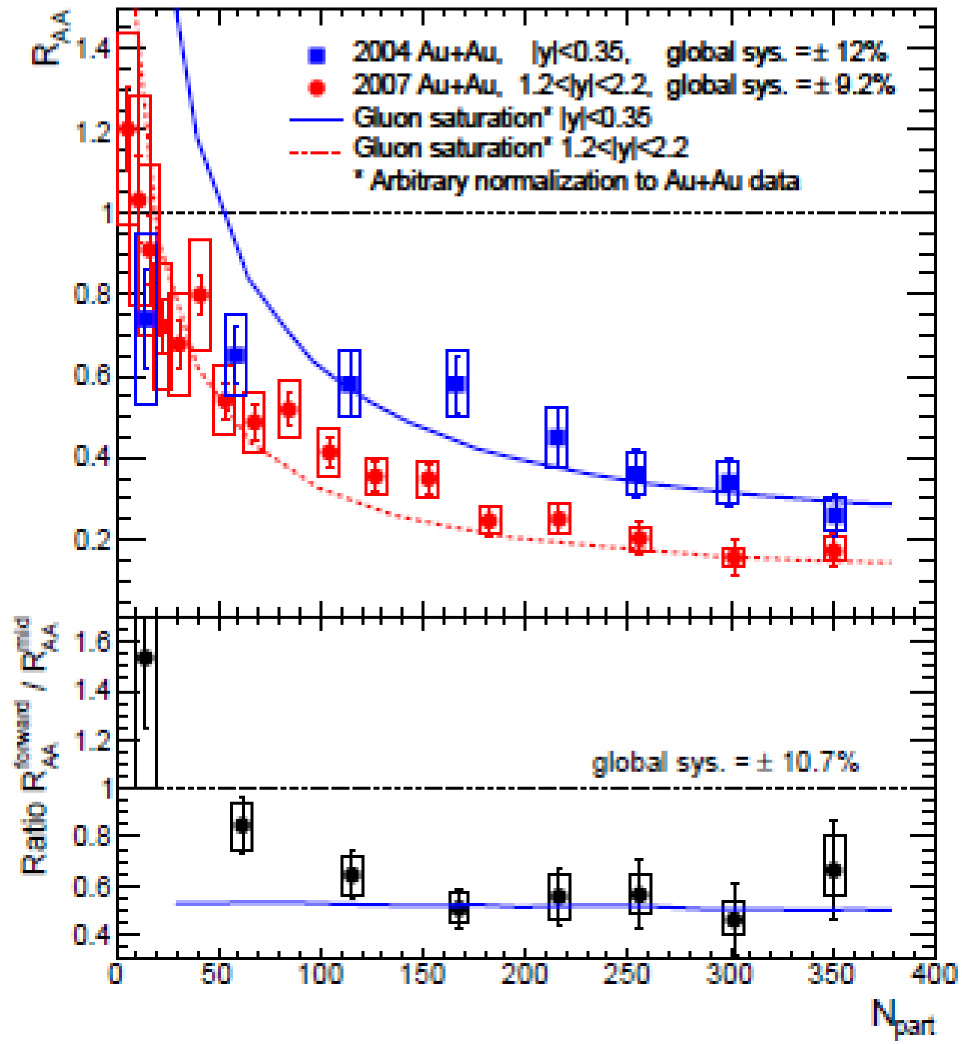
Comparisons to models (1): CGC

CGC calculation reproduces qualitatively the magnitude of the suppression and its rapidity dependency

However this calculation has one free "normalization factor", <u>fitted</u> to the data.

<u>Calculations</u> of this normalization are in progress. They should reduce by x 2 the effect of the CGC (private communication), but the forward vs mid-rapidity difference remains.

arXiv: 1103.6269

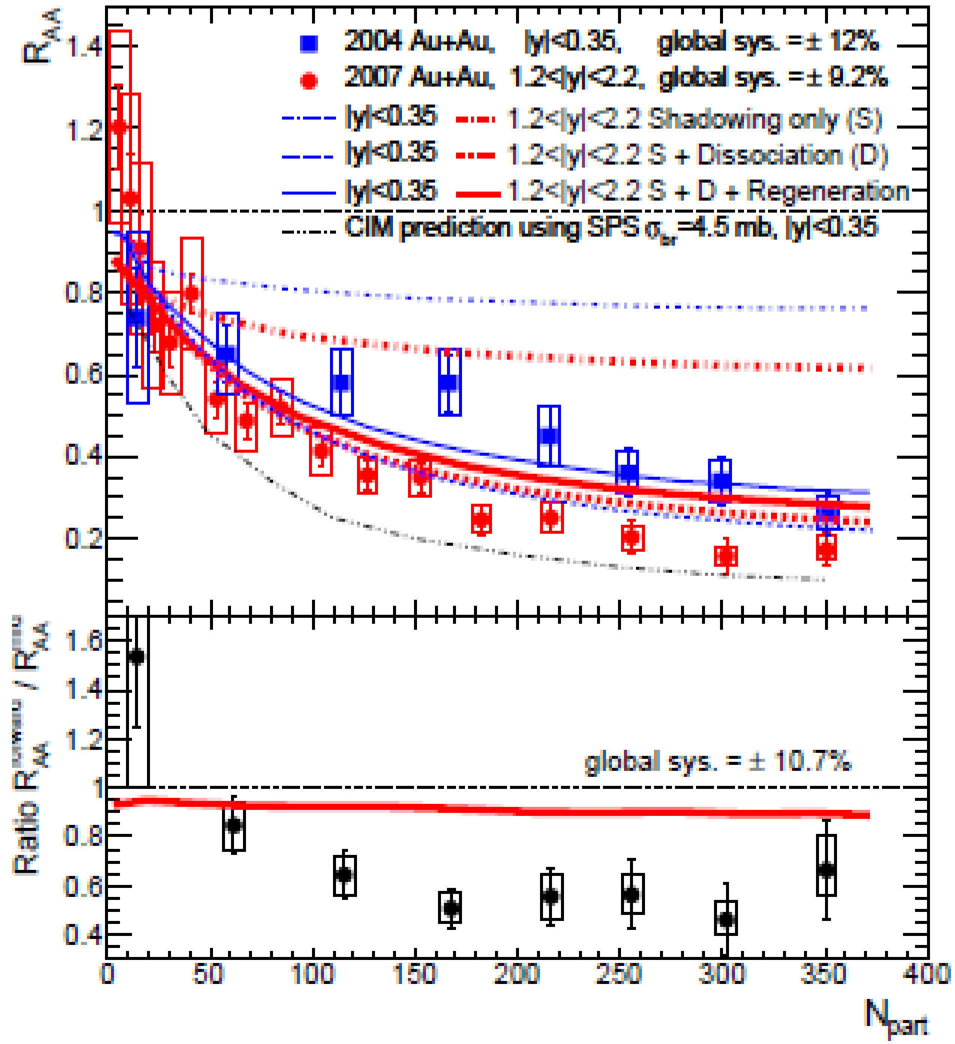


Comparison to models (2): Comovers

Ingredients to Capella et. al. calculation:

- Cold nuclear matter estimates guided by PHENIX d+Au (including parametrized shadowing and small $\sigma_{breakup}$)
- J/ψ interaction with a co-moving medium of unknown nature, characterized by its density and a σ_{co} interaction cross-section
- J/ψ regeneration by uncorrelated cc pair recombination

arXiv: 1103.6269



Comparisons to models (3): Regeneration

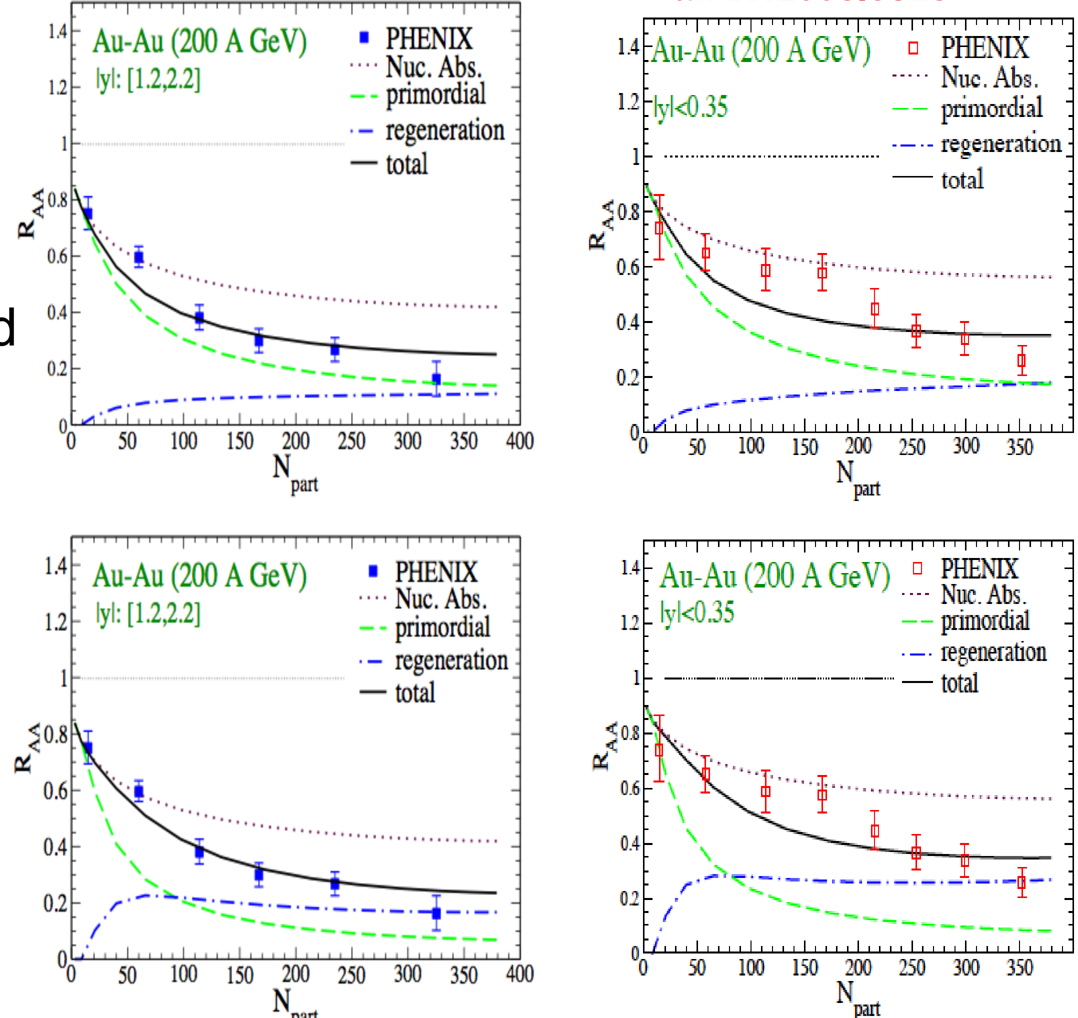
Ingredients to Zhao and Rapp calculation:

- Cold nuclear matter estimates guided by 2008 PHENIX d+Au R_{CP} data.
- prompt J/ψ dissociation in QGP
- J/ψ regeneration by uncorrelated $c\bar{c}$ pair recombination
- Feed-down contributions from B

Top: Strong binding (T_d=2T_c)
Bottom: Weak binding (T_d=1.2T_c)

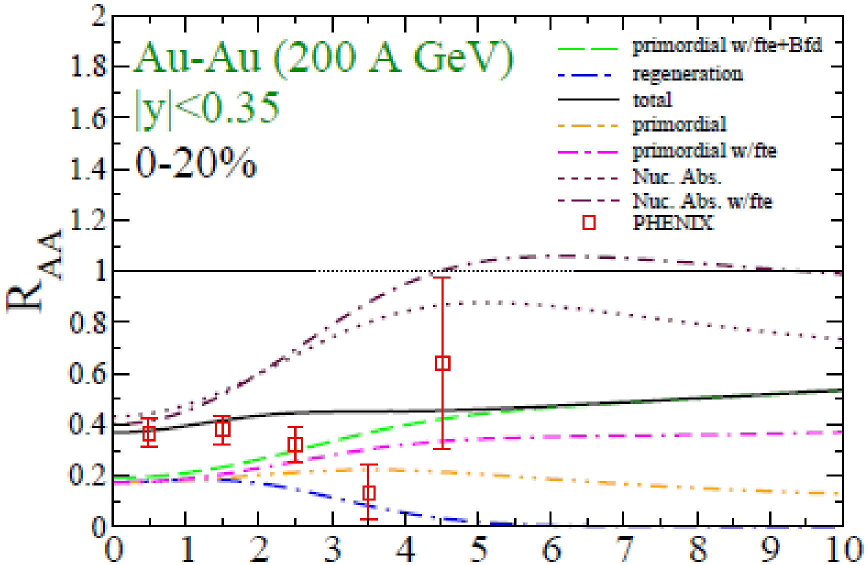
One notes that a large fraction of the mid/forward difference is accounted for by CNM

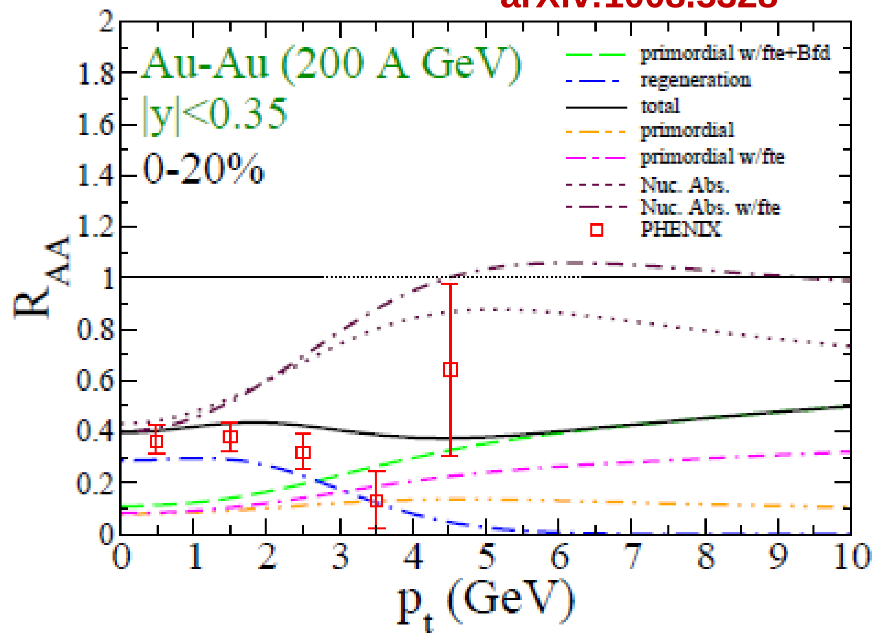
arXiv:1008.5328



Comparisons to models (3): p_T dependence

arXiv:1008.5328





Same calculation from Zhao and Rapp as for previous slide

Left: Strong binding (T_d=2T_c)
Right: Weak binding (T_d=1.2T_c)

fte: Formation Time Effects

Qualitative agreement is achieved (with weak dependency on J/ψ binding strength), but data are statistically limited.
Same is true at forward rapidity.

J/ψ R_{CP} vs N_{part} at lower energy

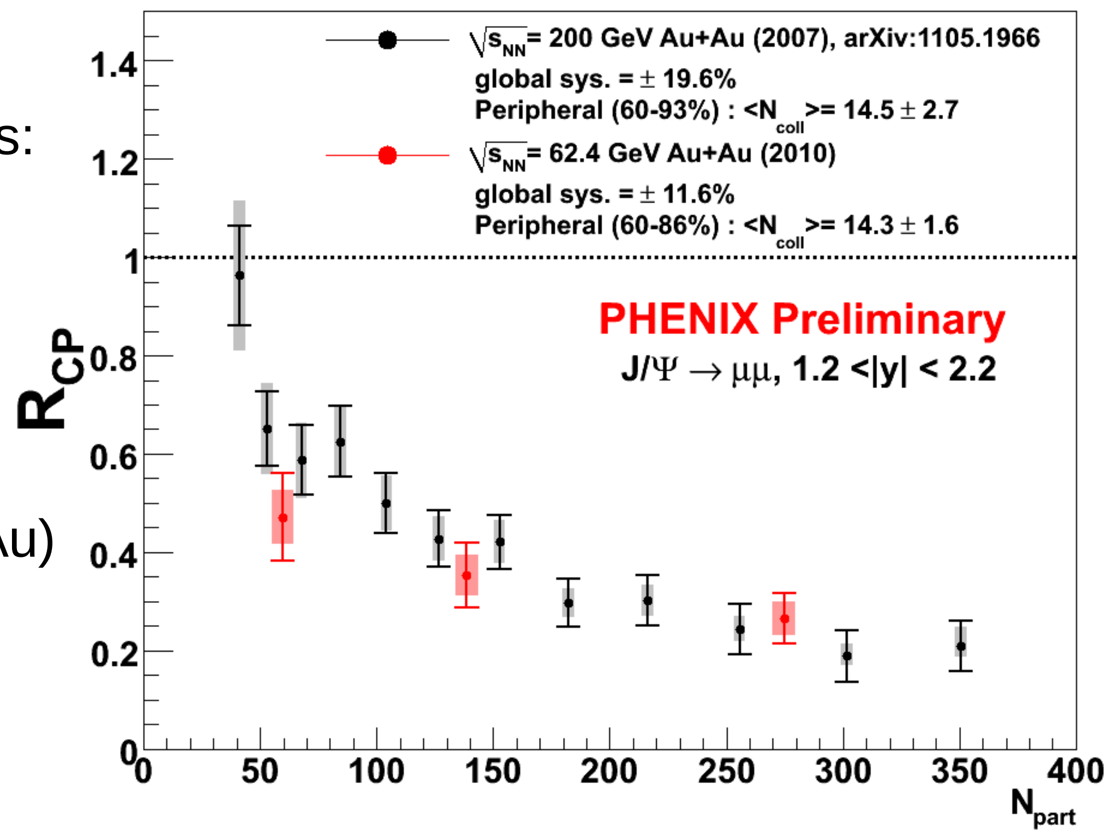
J/ψ production has also been measured at $\sqrt{s_{NN}}$ = 62.4 GeV, (and 39 GeV).

It is interesting because energy density is smaller; as well as *x* region covered by PHENIX arms: less shadowing is expected.

Missing are:

- a proper p+p reference (hence R_{CP})
- an estimate of CNM (from d+Au)

Abhisek Sen QM2011



Conclusion (1)

Two approaches emerge for describing Cold Nuclear Matter effects on J/ψ production in d+Au collisions:

- <u>(poorly constrained) npdf + initial energy loss + $\sigma_{breakup}$</u>
  it cannot describe latest PHENIX data at forward rapidity. Additional effects might be at play (~~such as initial state energy loss~~).

- <u>gluon saturation CGC</u>
  it provides an alternative description of the collision at low x_2 (y>0) and (at least qualitative) explanations to some of the observed effects, e.g. forward/mid difference in AA.

None of these approach fully describes the d+Au data

None of these approach can account for the suppression observed in Au+Au

$\Rightarrow$ anomalous J/ψ suppression in Au+Au is observed

Conclusion (2)

Several models are available to try describe the Au+Au J/ψ data.
They need to account for many effects to achieve ‘qualitative’ agreement.

Notably: observed forward/mid rapidity differences might be largely accounted for by CNM effects.

J/ψ suppression beyond CNM effects is:

- Non zero
- Roughly consistent with suppression observed at SPS
- Smaller than expected from SPS based models, and requires the use of extra component(s)

It is crucial to add more measurements (p_T dependence, feed-down contributions, higher/lower energy); and to ask models to reproduce all available observables.

Comparisons to LHC results will be very instructive, especially when CNM effects will be measured at this energy.